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CARBON DIOXIDE REMOVAL SYSTEM OF THE REGENERABLE SOLID ADSORBENT TYPE

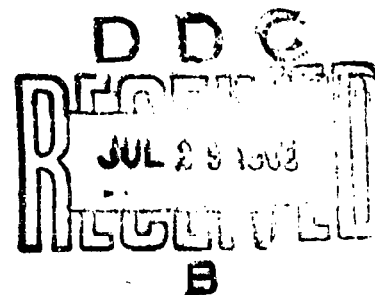
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*General American Research Division
General American Transportation Corporation*

MARCH 1969



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FOREWORD

This report was prepared by the General American Research Division of the General American Transportation Corporation, 7449 North Natchez Avenue, Niles, Illinois, under Contract AF 33(615)-1369. The contract was initiated by the Aerospace Medical Research Laboratory, Wright-Patterson Air Force Base, Ohio, under Project No. 6373, "Equipment for Life Support in Aerospace," Task No. 637305, "Analysis and Integration of Life Support Systems". Mr. J. Arthur Brown, Biotechnology Branch, Life Support Division, Biomedical Laboratory* served as Contract Monitor.

The research and development work reported herein was performed for the General American Transportation Corporation by Messrs. G.A. Remus, P.P. Nuccio, and R.J. Honegger. Work under the contract was initiated in February 1964 and was completed in December 1967.

This report is catalogued by General American Research Division as their final report number 1253-8590.

This technical report has been reviewed and is approved.

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Commander
Aerospace Medical Research Laboratory

*The Biotechnology Branch, Life Support Division, and Biomedical Laboratory were abolished during a reorganization in December 1968.

ABSTRACT

The development of a regenerable carbon dioxide removal system is discussed. The system utilizes solid zeolites to adsorb carbon dioxide and silica gel for predrying the gas stream. The system is completely regenerable, operates automatically and continuously, and provides for storage of the removed carbon dioxide. It is operable over a wide range of cabin environments and provides flexibility in varying the system operating parameters. It may be used to determine the thermodynamic requirements of a flight-type system for a particular cabin gas composition. The system can remove the carbon dioxide from four crewmen and maintain the carbon dioxide partial pressure between 4 and 5 mm Hg absolute at atmospheric pressure operation and between 6 and 7 mm Hg when operating at 350 mm Hg total pressure. It has this removal capacity when the cabin atmosphere is composed of 13 mm Hg water vapor partial pressure, 160 mm Hg oxygen partial pressure and either nitrogen or helium as the makeup gas. An external control console is provided which permits the system to be operated in an unmanned chamber. The system is not optimized for power and weight; as a laboratory model the total average power required is 4000 watts and the total weight including the mounting frame is 250 pounds.

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SECTION I

INTRODUCTION

BACKGROUND

Long duration aerospace missions will require that food, water, and oxygen be recovered onboard the spaceship rather than carried as initial supplies. This results from the lower weight penalty of regenerable systems over initial supply systems. The most logical approach to supplying oxygen is to recover oxygen from the exhaled carbon dioxide. The specific systems which carry out this reduction process require that the carbon dioxide be supplied in a concentrated form (in the area of 85 to 95% pure carbon dioxide) as compared to the 1 to 2% concentration which exists in the spacecraft atmosphere. Therefore, a system is needed which will remove carbon dioxide from the atmosphere and supply it to a carbon dioxide reduction system in concentrated form.

Various processes have been investigated and/or developed for carbon dioxide removal. Limiting this discussion to those processes which are compatible with a carbon dioxide reduction system these would include:

- a) adsorption by solid zeolites
- b) charcoal adsorption
- c) selective permeation membranes

The most significant research and development advancement has been with the solid zeolites. Based on development to date, charcoal adsorption systems and membrane systems impose higher weight penalties than the solid zeolite systems.

The Regenerable Carbon Dioxide Removal System described in this report was designed for use with the existing Life Support Systems Evaluator (LSSE) (Reference 1) at the Life Support Systems Division of the Aerospace Medical Research Laboratory. The LSSE serves as a research tool for determining the technical feasibility of techniques and principles involved in the operation and design of life support equipment through integrated evaluation studies. These studies are planned to develop optimal life support systems, including respiratory equipment, nutritional support, and waste management. The broad spectrum of work involved in biologists and bioastronautics can also be studied. Environmental parameters are normally monitored utilizing consoles having special purpose gas analysis equipment, total pressure sensors, temperature and humidity sensors, each complete with visual display and recorder printout. (Reference 2) These consoles, as described, also include the necessary communications and closed circuit television for simultaneously monitoring the well-being of human subjects confined to the LSSE.

SYSTEM REQUIREMENTS

The performance requirements specified by the Aerospace Medical Research Laboratory for the Carbon Dioxide Removal System were as follows:

1. Capacity to collect carbon dioxide output of 4 crewmen (4.72 kg/day)

and maintain carbon dioxide partial pressure not exceeding 7.6 mm Hg.

2. Operate in cabin atmosphere of $25.5 \pm 1.0^{\circ}\text{C}$ and cabin total pressure between 350 and 775 mm Hg with an oxygen partial pressure of 160 mm Hg and either nitrogen or helium diluent.
3. Operate in cabin water vapor partial pressure of 13.0 mm Hg, maximum.
4. Desiccant subsystem required to maintain a dewpoint below -46°C (63ppm) for six continuous days.
5. Recover 85% of the carbon dioxide available at a minimum purity of 90% average and store at 15.5 to 17.0 psia.

APPROACH

Solid zeolites have the capability to adsorb a gas or vapor from a mixture. Certain zeolites preferentially adsorb carbon dioxide in the absence of water vapor. The adsorption capacity depends on the partial pressure of the carbon dioxide and on the temperature of the zeolites. When subjected to elevated temperature and vacuum the zeolites are desorbed of concentrated carbon dioxide. To prevent the zeolites from adsorbing water vapor in place of carbon dioxide silica gel beds are required to dehumidify the inlet gas prior to carbon dioxide adsorption.

Various factors governed the design approach of the carbon dioxide removal system. Primary among these, in addition to the specific requirements given above were the following:

1. Reliability and simplicity of automatic system operation.
2. Component and overall system arrangement for accessibility and ease of maintainability, or modification if required.
3. Minimal weight, volume and power, but without compromise to performance, reliability, ease of operation, simplicity or maintainability.

A system was first assembled and tested in air at 7.7 psia and at 14.7 psia. The results of this program are described in Reference 3 .

Based on the above guidelines, the system performance requirements, and the background experience gained in operating the original system, it was determined that (1) the carbon dioxide removal system must include heat exchangers in both the desiccant and zeolite beds, (2) the system should include an inlet dehumidifier to strip off the water vapor which is condensable at normal cabin air conditioning temperatures, and (3) thermal independence should be provided (by suitably located coolers) between the zeolite and desiccant subsystem which is desirable for its installation in a laboratory test simulator.

SECTION II

DESIGN AND ASSEMBLY

GENERAL DESCRIPTION

The Regenerable Carbon Dioxide Removal System is comprised of a desiccant subsystem, a zeolite subsystem, and auxiliary valves, pumps, heat exchangers, and controls. Two beds are used in both the desiccant subsystem and zeolite subsystem to provide continuous operation. In the desiccant subsystem one bed adsorbs water vapor from the incoming gas stream while the other bed is being desorbed by the exiting gas. Similarly, one zeolite bed adsorbs the carbon dioxide in the process gas stream while the opposite bed is being vacuum desorbed. The auxiliary components provide the desired process gas flow rates, temperatures, and pressures for the desiccant beds and zeolite beds to function effectively.

The schematic flow diagram for the Regenerable Carbon Dioxide Removal System is shown in Figure 1. Referring to this diagram, the normal operation of the system is as follows. Cabin gas enters the dehumidifier through a small independent blower which moves approximately four times the quantity of gas than that which flows through the system. The cabin gas is cooled and the water vapor which is condensable at normal air conditioning temperatures is stripped off as condensate. The major portion of the dehumidifier flow is returned to the cabin. The process gas flow is drawn from the dehumidifier into the adsorbing desiccant bed (right) where the gas is dried to -46°C dewpoint or lower. The desiccant is capable of achieving this dewpoint through the utilization of an in-bed heat exchanger which removes the heat of wetting and any residual heat from a previous regeneration cycle. After the desiccant pre-drying process, the gas passes through the desiccant gas switch valve and then through a cooler to the blower. The blower is the prime mover for the process gas stream. A gas cooler downstream of the blower removes its heat of compression. The cool, bone-dry gas then passes through the zeolite gas switch valve to the adsorbing zeolite bed (left) where the carbon dioxide is adsorbed on the solid zeolite pellets. Since the zeolite adsorption capacity is dependent on temperature and pressure, the control of the bed temperature is aided by an in-bed heat exchanger. The carbon dioxide free gas leaves the zeolite bed through a check valve and passes through a gas cooler before entering the desiccant gas heater. The gas cooler removes any undesirable heat in the gas stream and, in this manner, provides thermal independence between the desiccant and zeolite subsystems. The thermostatically controlled desiccant gas heater provides part of the thermal energy required to regenerate a desiccant bed. The warm dry gas exiting from the heater passes through the desiccant gas switch valve and then to the regenerating desiccant bed (left). Utilizing the heat from an in-bed heat exchanger the desiccant

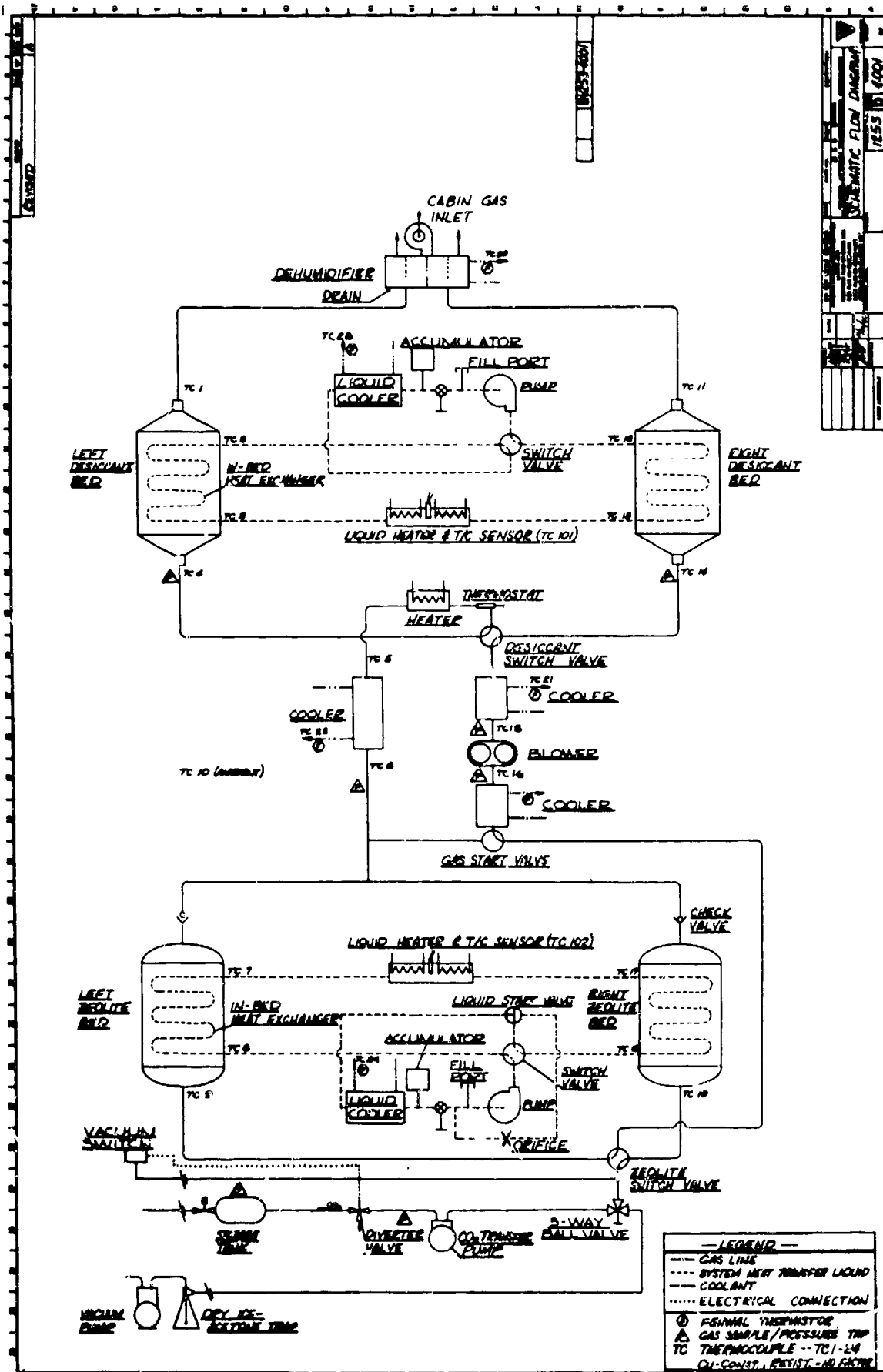


Figure 1. SCHEMATIC FLOW DIAGRAM

gives up the water vapor it adsorbed on the previous cycle. The gas then exits through the dehumidifier housing; no processing occurs on the return flow through the dehumidifier so the process gas stream exits from the system at essentially the same temperature it entered. While the adsorbing zeolite bed is removing carbon dioxide from the process gas stream, the opposite bed is being regenerated by heat and vacuum desorption. To accomplish this, the regenerating zeolite bed (right) is isolated from the system by a check valve in its gas duct. The carbon dioxide transfer pump initially discharges the interstitial gases from the zeolite bed back to the cabin. When the necessary desorption vacuum is reached, the diverter valve is actuated by the vacuum switch. The desorption gas flow is then directed to the carbon dioxide storage tank. Periodically the switch valves are operated by a signal from a cycle duration timer. The beds then function as their counterpart did on the previous cycle and vice versa. A detailed description of the components and controls is given in the System Assembly portion of this section.

A heat transfer liquid loop is employed to control the temperature in each desiccant bed and a separate loop is used in the zeolite subsystem. The flow arrangement is the same for each liquid loop. Starting at the pump inlet, the flow sequence is liquid pump, liquid switch valve, bed being cooled, liquid heater, bed being heated, then the opposite passages of the liquid switch valve, liquid cooler, and back to the pump. In addition the zeolite loop only has a manual start valve with a downstream orifice to permit part of the flow to bypass the cooler during start-up. In each loop, an accumulator is connected by a tee in the cooler to pump line. While the flow does not normally pass through it, the accumulator allows for liquid expansion due to temperature variations.

In start-up operation the primary objectives are to remove all moisture from the zeolite beds, and similarly to prepare the desiccant beds for removing the water vapor from the incoming gas stream. By switching the gas start valve, the gas stream bypasses the zeolite subsystem and the desiccant beds are progressively desorbed by cycling the flow direction through the beds. Also, for start-up operation the liquid start valve in the zeolite liquid loop is turned so that the majority of the liquid flow bypasses the liquid cooler, and the carbon dioxide transfer pump and storage tank are isolated from the zeolite beds by the three way ball valve. This valve provides a flow path to the vacuum pump-freeze trap system located external to the cabin. This system, in conjunction with the heat added by the in-bed heat exchanger removes any residual water in the zeolite beds. The detail procedures for start-up operation are described in the Operating Instructions and Maintenance Manual (Reference 4).

DESIGN CALCULATIONS

In order to insure system design adequacy, calculations were made particularly in support of the desiccant bed and zeolite bed sizing and vacuum desorption requirements. The calculations thus permitted proper sizing and selection of components so that when integrated into the entire system overall reliability, simplicity and automatic system operations were achieved. The overall packaging assembly was generated from the sizing calculations and configuration requirements were established for each system component.

Desiccant Bed Sizing

The desiccant beds were designed to provide dry air having a dew point of -80°F at atmospheric pressure. At an inlet temperature of $50-55^{\circ}\text{F}$, saturated, the incoming air contains 0.0085 pounds of water per pound dry air. The nominal volumetric flow rate is based on adequate carbon dioxide adsorption by the zeolite beds and was determined to be 12 cu ft per minute (see page 8).

At 50°F , and saturated, the useful capacity of silica gel for holding water is 7% by weight for an outlet dew point of -80°F (Reference 5). At 14.7 psia and with air flowing at 12 cu ft per minute the water flow rate is:

$$\begin{aligned} w &= (12 \text{ ft}^3/\text{min}) (0.0755 \text{ lb air}/\text{ft}^3) (0.0085 \text{ lb H}_2\text{O}/\text{lb air}) (60 \text{ min}/\text{hr}) \\ &= 0.46 \text{ lb H}_2\text{O}/\text{hr}. \end{aligned}$$

To provide a water-holding capacity for this rate approximately 6.5 pounds of silica gel are required for each hour of operation. In addition, a one-second stay time is required to allow for a drying zone in which active adsorption takes place at a bulk density of 45 pounds per cu ft. The weight of silica gel in each bed for this zone is:

$$(0.2 \text{ cu ft per second}) (1 \text{ second}) (45 \text{ lb}/\text{ft}^3) = 9 \text{ lbs.}$$

The total weight of each bed is as follows, where "N" is the number of minutes each bed is on stream:

$$W = 9 + (6.5) (N/60) \text{ lb}$$

A nominal cycle time of 30 minutes was used, but this was varied during actual tests. For this cycle time the weight of silica gel in each bed is:

$$W = 9 + (6.5) (30/60) = 12.3 \text{ lbs}$$

The volume occupied by this weight of silica gel is as follows:

$$V = 12.3/45 = 0.275 \text{ ft}^3$$

The superficial linear velocity should be 30 feet per minute (Reference 6). At a volumetric flow of 12 cu ft per minute the required dimensions of the cylindrical bed are:

$$A = 12/30 = 0.4 \text{ ft}^2$$

$$D = \sqrt{0.4/0.78} = 0.71 \text{ ft} = 8.5 \text{ in}$$

$$L = 0.275/0.4 = 0.69 \text{ ft} = 8.3 \text{ in}$$

The actual bed dimensions were 8.5 inches in diameter by 10.5 inches long to allow for space occupied by the heat exchanger. Each bed was filled with 12 pounds of silica gel, 12-28 mesh, grade 08, Davison Chemical Division, W.R. Grace and Co.

Zeolite Bed Sizing

The average carbon dioxide adsorption rate of 10.4 pounds per day (0.433 pounds per hour) determines the weight of solid zeolites needed and the air flow rate required through the bed. The bed must have the capacity to remove carbon dioxide at this rate while adsorption continues.

At a carbon dioxide partial pressure of 7.6 mm Hg, a total pressure of 14.7 psia, and a superficial linear air velocity of 30 feet per minute, the carbon dioxide adsorption rate averages 0.080 lb carbon dioxide per hour-pound zeolites under ideal conditions, i.e., (1) the zeolites are initially free of all carbon dioxide and water, (2) the inlet air is dried to -80°F dew point or lower, and (3) the zeolites are at a uniform temperature of 70°F or lower. Thus if the zeolites were fully utilized the weight continuously needed for adsorption would be:

$$W = 0.433/0.080 = 5.4 \text{ lbs.}$$

In actual use the beds will be cycled through adsorption; because the beds are not as efficiently utilized in such a process the average carbon dioxide adsorption rate decreases to approximately 0.043 lb carbon dioxide per hour per pound zeolite at a superficial air velocity of 30 cu ft per minute. The adsorption rate could have been increased by operating at higher air flow rates, but this would have necessitated drying a larger volume of air and would have penalized other parts of the system.

For these conditions the bed size and volumetric flow rate are as follows:

$$W = 0.433/0.048 = 9.0 \text{ lb of zeolites}$$

$$V = 9.0 \text{ lb}/45 \text{ lb per ft}^3 = 0.20 \text{ ft}^3, \text{ bulk volume}$$

The carbon dioxide dynamic loading capacity of the zeolites on an average cycle basis is approximately 2-1/2% by weight. The 9.0 lbs of zeolite thus holds an average of 0.22 lb of carbon dioxide and can be on stream for approximately 30 minutes during adsorption. These data are in general agreement with tests performed at General American Research Division and with published capacity data (Reference 7). For a recommended stay time of one second, the resulting flow is:

$$\text{Flow} = \text{vol}/\text{stay time} = 0.20 \text{ ft}^3/\text{sec} = 12.0 \text{ ft}^3/\text{min}$$

The dimensions of the cylindrical bed are:

$$A = (12.0 \text{ ft}^3/\text{min})/(30 \text{ ft}/\text{min}) = 0.4 \text{ ft}^2$$

$$D = \sqrt{4A/\pi} = \sqrt{0.40/0.785} = 0.71 \text{ ft} = 8.5 \text{ in}$$

$$L = 0.20 \text{ ft}^3/0.40 \text{ ft}^2 = 0.5 \text{ ft} = 6.0 \text{ in}$$

The heat exchanger within the bed occupies a volume small by comparison to the overall volume but causes the actual dimensions to be slightly larger; to provide for the volume, and to allow for anticipated looser packing of the zeolites around the heat exchanger the actual zeolite bed dimensions were 8.5 inches in diameter by 8.9 inches long. Each bed was filled with 12 pounds of zeolites in the form of 1/16 inch diameter extrusions 1/16 to 3/16 inch long, type 5 AXW Molecular Sieves, Linde Division, Union Carbide Company.

Vacuum Desorption Requirements

The vacuum pump was sized on the basis of the more demanding of two requirements, (1) desorbing bed pump-down time, and (2) carbon dioxide transfer rate out of the bed during desorption.

The void volume in the zeolite bed canister and piping is approximately 0.50 cu ft. To pump this volume down to a given absolute pressure requires removal of a corresponding volume of gas, related to the void volume by the initial and final pressures, and according to:

$$V = V_o \ln(P_o/P)$$

where V = Volume of gas

V_o = Void volume

P_o = Initial pressure

P = Final pressure

From this formula the final pressure is related to volume removed.

P (mm Hg Abs)	50	10	7.6	3.8
V (ft ³ removed)	1.1	2.2	2.3	2.6

For example, if the pump-down time is required to be 1 minute and final pressure 7.6 mm, the vacuum pump displacement would have to be 2.3 cfm, or conversely if the pump displacement were 1.15 cfm it would take 2 minutes to pump down to 7.6 mm.

Because the carbon dioxide should be 99% pure, containing less than 1% air by volume, a final pressure of 15 mm Hg absolute will be needed at the end of pump-down. The pump-down time should be of the order of 1 minute or less. Consequently a pump with a minimum 2-cfm displacement is needed for this requirement.

To provide adequate desorption and to allow for variations in heating the bed to desorption temperatures, the carbon dioxide removal capacity should be high enough to permit complete desorption in 15 to 18 minutes of a 30 minute cycle, leaving the remainder of the cycle time as a safety factor. This removal capacity is equivalent to a mass flow rate of 0.014 lb carbon dioxide per minute.

The volume flow rate is dependent upon temperatures and pressure. Assuming a temperature of either 300°F or 70°F, if cooled, and a mass flow rate of 0.014 lb carbon dioxide per minute, the carbon dioxide volumetric flow from the bed varies with bed pressure as follows:

P (MM Hg abs)		100	50	25	10	7.6	3.8
V (ft ³ /min) at 300°F :	1.34	2.44	4.87	14.30	16.0	32.2	
V (ft ³ /min) at 70°F :	0.85	1.70	3.40	8.52	12.5	22.4	

Adsorption capacity data on zeolite material indicates that the desorption pressure should be below 50 mm, preferably as low as 10 or 15 mm Hg absolute. The table thus shows that a 3 cfm pump will remove carbon dioxide at approximately 40 mm at 300°F or 30 mm if the inlet line to the vacuum pump is cooled to 70°F; a 6 cfm pump will provide approximately 20 and 15 mm Hg absolute, respectively.

From these sizing evaluations the vacuum pump should have a displacement capacity of 5 to 6 cfm for pump-down to approximately 20 mm Hg.

SYSTEM ASSEMBLY

The general system configuration, assembled and mounted for operation inside the simulator is shown in Figure 2. The two desiccant beds are located at the upper portion of the unit to facilitate the arrangement of the ductwork. The zeolite beds are located in the lower area of the unit. The associated liquid loop components are located in close proximity to the respective desiccant and zeolite beds.

The processing beds and auxiliary components are connected by 1-inch outside diameter by 0.035 wall tubing. Flexible sections of tubing are appropriately spaced to allow for thermal expansion between the components. The tubing to component joints is made through bolted flanges with an O-ring seal. The entire gas flow path through the zeolite subsystem and through the adsorbing portion of the desiccant subsystem must be leak tight to prevent water vapor contamination from cabin gas in-leakage. The rigid tubing with expansion sections and bolted flanges achieves this leak tight requirement.

The system controls are packaged in a separate console which is located external to the cabin. This console houses the timers, liquid heater controls, and all indicator lights and control switches. A secondary display panel is located on the front of the unit at eye level. This panel includes parallel indicator lights and instrumentation applicable for observation by test-crew members. The power control terminal board is located directly above the display panel and the thermocouple terminal board directly below the panel.

Desiccant Bed Assembly

The desiccant container is cylindrical and closed by a fixed elliptical head at the lower end. A removable cover, of conical section, closes the upper end. A mechanical V-type clamp holds the cover in place.

The container was fabricated from 0.025 inch stainless steel. Stainless steel was the most suitable material for minimum weight and for the fabrication requirements imposed by the heat exchanger feed-through interface seals. Each bed incorporates a finned tube heat exchanger (see page 12) to provide the necessary temperature control encountered with the wide range of cabin gas compositions.

A perforated metal screen and fiber filter were placed at both ends of the beds. The screens retain the desiccant particles, and the filter prevents fine particles and dust from being carried with the gas stream. The filters also aid in equalizing gas flow distribution over the entire bed area. An uneven velocity profile through the bed would be detrimental to performance because at points of high velocity a channel through the bed could develop and allow unprocessed gas to leave the beds.

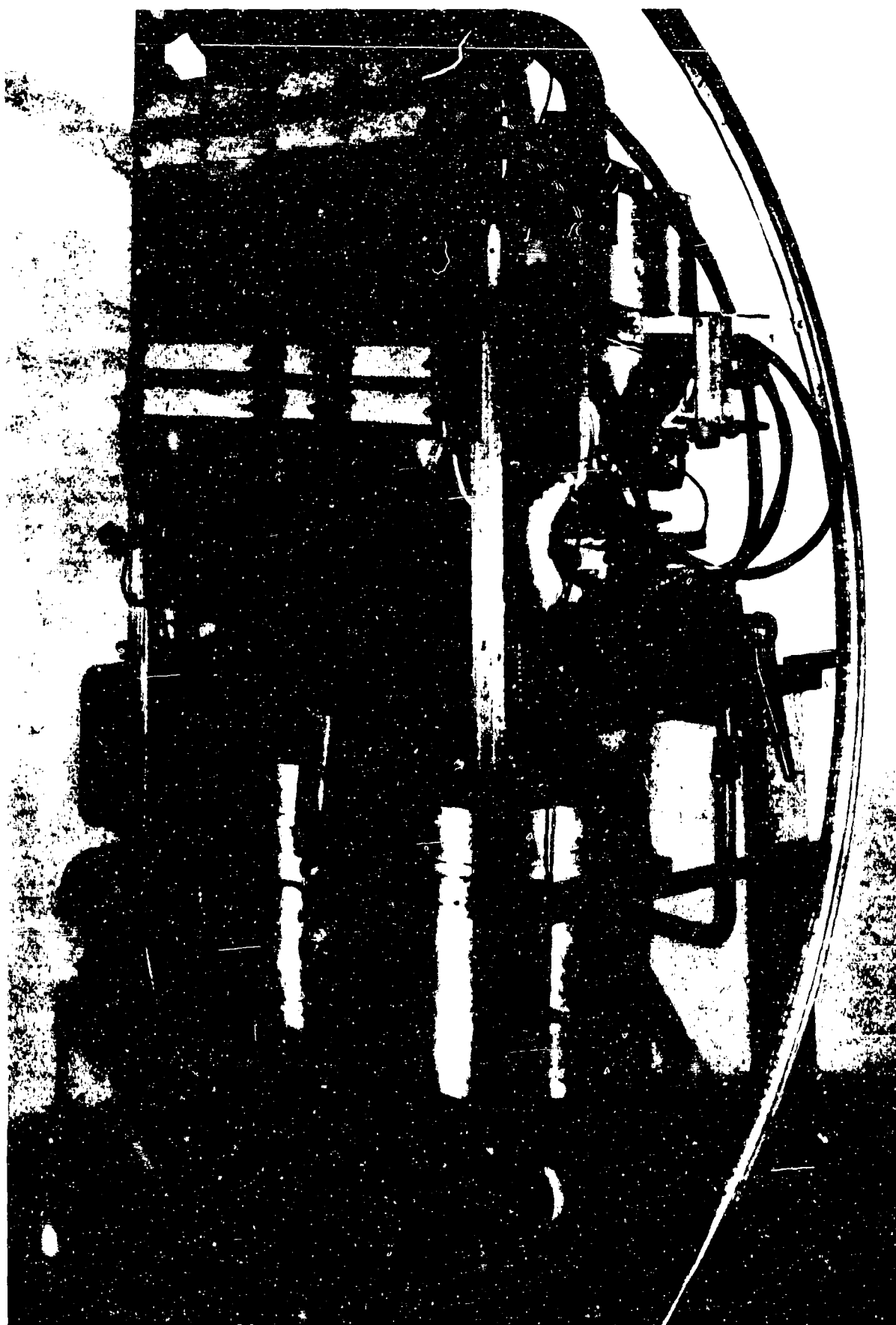


Figure 2. CARBON DIOXIDE REMOVAL SYSTEM

A layer of polyurethane insulation was foamed in place around the inner container to reduce heat losses to ambient, and a thin aluminum outer skin covers the entire assembly and protects the insulation from mechanical damage. The skin also conveniently distributes the clamping load, applied through mounting brackets, through the insulation and to the inner shell.

Zeolite Bed Assembly (Figure 3)

The zeolite canisters are vacuum-tight pressure vessels, that include finned-tube heat exchangers designed so that no particle of zeolite within the bed is farther than 1/8 inch from a heat transfer surface.

The inner shell is a 0.025 inch gauge weldment of 304 stainless steel. The gauge and shape were sized to prevent buckling under 15 psi pressure applied externally. One elliptical end of the canister is removable and is sealed to the canister by a silicone rubber "O" ring and a V-band clamp. Sealing is aided by the difference in pressure; the cover and main container are pushed together by the external pressure. Stainless steel was selected for the shell because its thermal conductivity is lower than that for any other chemically suitable metal.

An all-aluminum finned tube heat exchanger runs through the entire volume allotted to zeolites within the inner shell. When the zeolites are poured into the canister they make intimate contact with the heat exchanger surface, and no point of any zeolite particle is more than 1/8 inch from the heat transfer surface. Performance of the liquid loop cycle is keyed directly to effective heat transfer between the finned tube heat exchanger and the zeolite particles.

Dual purpose screens and filters were used at both ends of the zeolite beds, having the same function as those in the desiccant beds. They serve to retain particles and dust, and to smooth the gas velocity profile across the bed.

Thermal losses from the inner shell are retarded by a three-inch composite layer of calcium silicate and polyurethane foam insulation suitable for temperatures up to 600°F. Like the desiccant canisters, a 0.063 inch thick unpainted aluminum outer skin covers the whole assembly and protects the insulation from mechanical damage. The skin serves to mechanically connect the two canisters and to distribute their weight through the attached mounting brackets.

In-Bed Heat Exchanger (Figure 4)

During desorption of carbon dioxide in normal cycled operation of the system the zeolites require heating from 70°F to between 300°F and 350°F, for either atmospheric or 350 mm Hg operation. To accomplish this in the normal

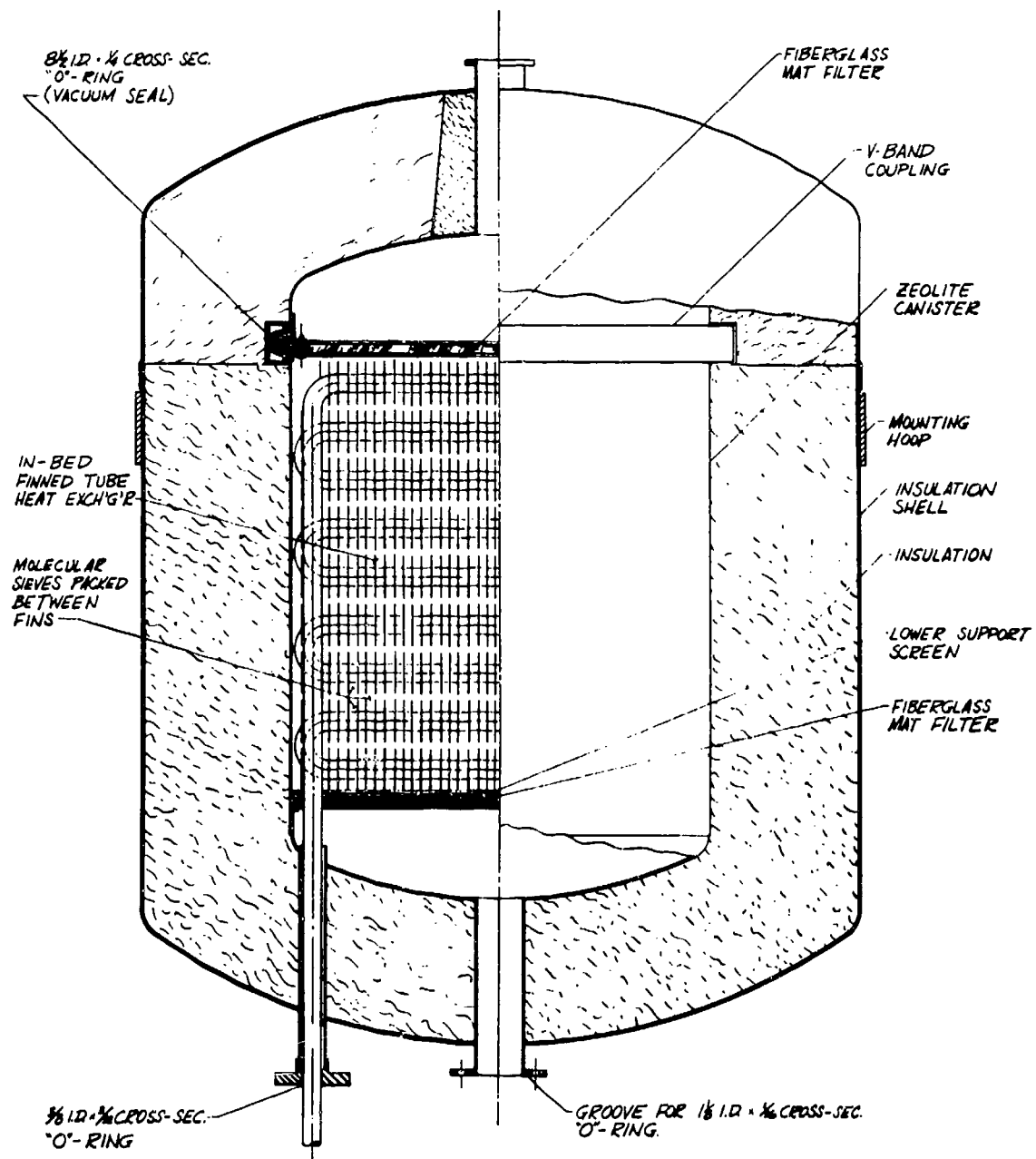
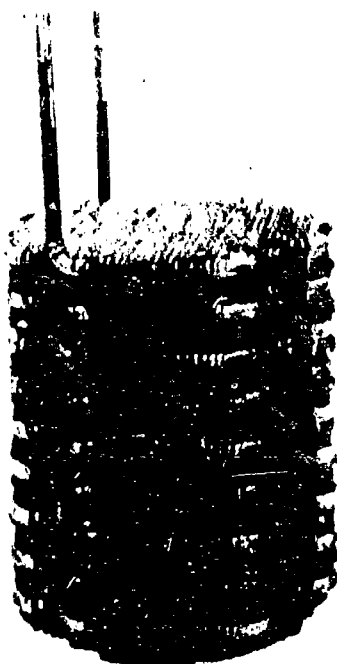


Figure 3. ZEOLITE BED ASSEMBLY



A



B

Figure 4. IN-BED HEAT-EXCHANGERS

cycle time, 30 minutes, a heat transfer liquid is heated to these levels and pumped through the finned-tube heat-exchanger in the zeolite bed. During initial desorption of water in start-up the beds require heating to 450°F; this is accomplished in the same manner with an increased cycle time and no intermediate cooling of the heat transfer liquid. Similarly, during adsorption of carbon dioxide the zeolites require cooling to 70°F. To accomplish this the same heat transfer liquid is cooled and pumped back through the in-bed heat exchanger.

The heat-exchanger was sized on the basis of the required zeolite bed weight and dimensions, the zeolite particle dimensions which physically limited the fin spacing selection, and a mathematical analysis relating heat-transfer to fin and tube size in conjunction with actual operating data from similar heat-exchangers built previously by General American Research Division. The configuration of the heat-exchanger is based on the need for rapid heating of the zeolite bed up to the required carbon dioxide desorption temperature.

The heat exchanger consists of nine separate layers of fins and tubes; each layer is circular, and is spaced 1/8 inch from the next layer. Only the final exit tube from each layer is connected in series to the next layer, and the fins in one layer are not connected to the fins in the next layer. The adsorbent lies in the 3/16 inch space between the fins, and the heat transfer liquid flows inside the tubing moving back and forth eight times in each layer before passing on in sequence to the next layer.

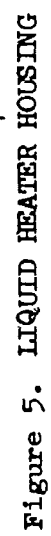
Identical units are used in each desiccant bed, employing the same heating and cooling techniques as when used in the zeolite beds. These heat exchangers were constructed throughout from aluminum and assembled by dip-brazing and welding.

Liquid Pump

Each liquid loop is a closed recirculating loop. The flow is provided by an adjustable stroke diaphragm pump. The diaphragm and pump head are constructed from Teflon®. The adjustable stroke mechanism allows for variable flow rates to be used in optimizing system parameters. A diaphragm-type pump eliminates dynamic seals and their associated maintenance. The pump operates from a 115-volt, 60-cps, single-phase source.

Liquid Heater

The recirculating liquid is heated by passing it through a heater housing as shown on Figure 5. Two identical cartridge heaters fit within the housing and are externally removable without draining the liquid from the housing or liquid loop. The thermocouple sensor for the temperature control and indicator is located equidistant from each heater and provides a symmetrical heating path for flow in either direction.



Liquid Cooler

The temperature of the heat transfer liquid leaving the desorbing bed can rise to as high as 300°F near the end of the cycle. Because this liquid is ultimately used to cool the adsorbing bed, it must be pre-cooled to 70°F or lower before it enters the bed. A liquid-to-liquid heat exchanger is used to accomplish the necessary pre-cooling.

The heat exchanger is in two identical sections with the heat transfer liquid and the coolant flowing in counter flow paths. The coolant used is a 50% water-glycol mixture circulated at 45°F, at a flow of 10 - 15 gal/hr. This flow is adequate to keep the heat-transfer liquid entering the adsorbing bed heat-exchanger at 70°F or lower.

Dehumidifier

A dehumidifier at the system inlet reduces the gas humidity before entering the adsorbing desiccant bed. The dehumidifier is constructed from a finned cooling coil housed within an aluminum shell. For each bed the gas enters at the top and makes a downward pass and an upward pass over the cooling coil. The bottom surface of the shell functions as a drip pan to collect the water vapor which condenses on the coil. The gas returning from the regenerating desiccant bed bypasses the cooling coil as it exits from the dehumidifier. The dehumidifier incorporates a low speed centrifugal blower to act as its independent air mover.

Blower (Figure 6)

Process gas is circulated through the system by a rotary-lobe blower. The blower operates at 1750 rpm and with the installed by-pass arrangement produces a system flow of 10 cfm. It is driven by a 3/4-hp motor which operates from a 208-volt, 3-phase, 60-cps source.

The motor-blower unit is housed in a leak tight vessel. This arrangement provides positive cooling flow over the motor and covers the rotating shaft and coupling. The motor and blower are lubricated with low vapor pressure grease to avoid emission of lubrication vapors into the gas stream.

Gas Cooler

Three gas coolers are used in the system to remove undesired heat and provide flexibility in system operation. A gas cooler is located upstream of the blower to provide for efficient blower operation with cool inlet gas. Effective carbon dioxide adsorption can only take place at low temperatures, so the blower heat is removed in a second cooler placed downstream of the blower. Another cooler is located in the return to the desiccant subsystem.

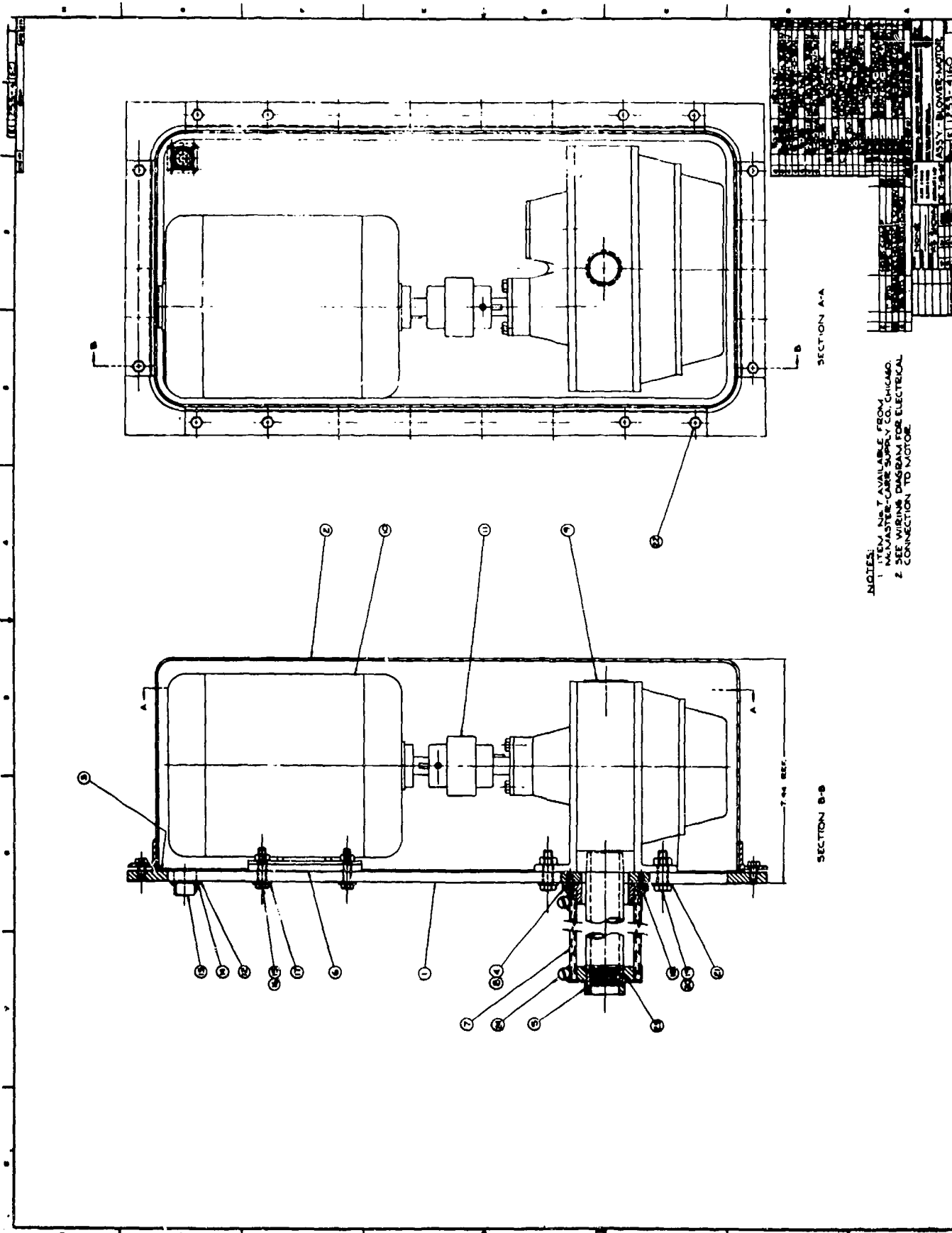


Figure 6. MOTOR-BLOWER ASSEMBLY

Each gas cooler is a gas-to-liquid heat exchanger and requires a liquid cooling loop. Construction of the cooler is conventional. The gas makes a single pass around a liquid-cooled, finned tube core, with the liquid making 14 passes in cross-flow inside of the core. The required liquid flow rate through each cooler is 0.3 gallons/minute, at a maximum temperature of 45°F and a specific heat of 0.8 - 1.0.

Desiccant Heater

The desiccant gas heater was designed to heat the gas entering the desorbing bed to approximately 275°F at 14.7 psia and 300°F at 360 mm Hg. The heater consists of a 4-inch long x 1/2-inch diameter sealed rod-type element with heat-dispersing fins, centered and supported within a 1-inch diameter tube. The outer tube is flanged on both ends and removable from the system. In operation the heater is rated at 300 watts, 115 volts, 60 cycles.

A thermostat downstream of the heater is set at approximately 325°F. The set screw for this thermostat is accessible through the insulation covering at its location above the desiccant valve. The thermostat serves to prevent overheating of the system; the operating temperature levels are determined primarily by the length of time the heater is allowed to remain on as controlled by the heater-duration timer.

Carbon Dioxide Transfer Pump

The carbon dioxide transfer pump is required to be an oil-free type so the carbon dioxide may be admitted to a carbon dioxide reduction system without oil contamination. Additionally, the carbon dioxide flowpath must be sealed to avoid in-leakage of air. Two sealed, diaphragm pumps with two cylinders per pump are used in three-stage flow with two cylinders operating in parallel for the first stage. The staged pump produced 6 mm Hg absolute at zero flow and 15 mm Hg absolute with 5 cfm inlet flow. Each pump motor (1/4 hp) operates from a 115-volt, 60-cps, single-phase source.

Carbon Dioxide Storage Tank

The carbon dioxide which is desorbed from the zeolite beds is transferred to a storage tank. The tank is 12 inches in diameter x 24 inches long with hemispherical ends.

Vacuum Pump

An oil-sealed, high vacuum pump is used in start-up to remove residual water from the zeolites. The pump produces 100 microns absolute or less when connected with an inlet dry-ice acetone trap. The vacuum pump and trap are located external to the cabin.

Desiccant Gas Valve (Figure 7)

Flow direction through the desiccant beds is reversed for every cycle by the four-port, 2-position, motor-driven desiccant switch valve. The valve, based on a compact wobble-plate configuration, was designed specifically for this application. The internal gas passages are large and free of sharp turns. The ports are accessible and located to facilitate piping to the other system components. A manual override is built into the valve, and the index points are 180° apart around a rotary motion. The handle is arrow-shaped to indicate the valve position. Indexing from one position to the other may be accomplished by turning the handle in a clockwise direction. The valve does not turn in the opposite direction.

High sealing capacity is not built into the desiccant switch valve because, for this application, it is not necessary and would introduce added resistance to the indexing motion. The pressure difference between ports is very low and inter-port leakage is insignificant to system performance. Lightweight design is employed throughout; the total weight of the valve exclusive of the 3/4 pound motor and transmission is thirteen ounces.

Zeolite Gas Valve (Figure 8)

The zeolite automatic switch valve is schematically identical to the desiccant valve; both have four-port, two-position configurations. The zeolite valve must operate under different conditions in two important areas. First, the zeolite valve must seal against a vacuum during desorption, and second, the volumetric flow required through the vacuum side of the zeolite valve is 5 cfm compared to 12 cfm through the normal air circulation side. To satisfy the sealing requirement, the moving element was designed as a spool which seats on O-rings, placed between ports in the valve body. In either index position the spool seals against two of the O-rings, and gas flow entering the center port is directed to one of the two adjacent ports. The other side port is open to the vacuum port either directly (left port) or axially through the spool (right port).

The spool is motor-driven through a speed reducer and pinion-rack mechanism to change rotary motion to axial motion. A manual override with a dual-direction ratchet to permit manual rotation of the valve handle in either direction to either bed position is designed into the valve. The automatic, electric indexing system will return the valve to the correct position in coordination with the zeolite bed heating and cooling cycle so that air flow is always directed through the cooled bed and a vacuum is always applied to the heated bed.

Gas Start Valve (Figure 9)

The function of the start valve is to bypass gas flow around the

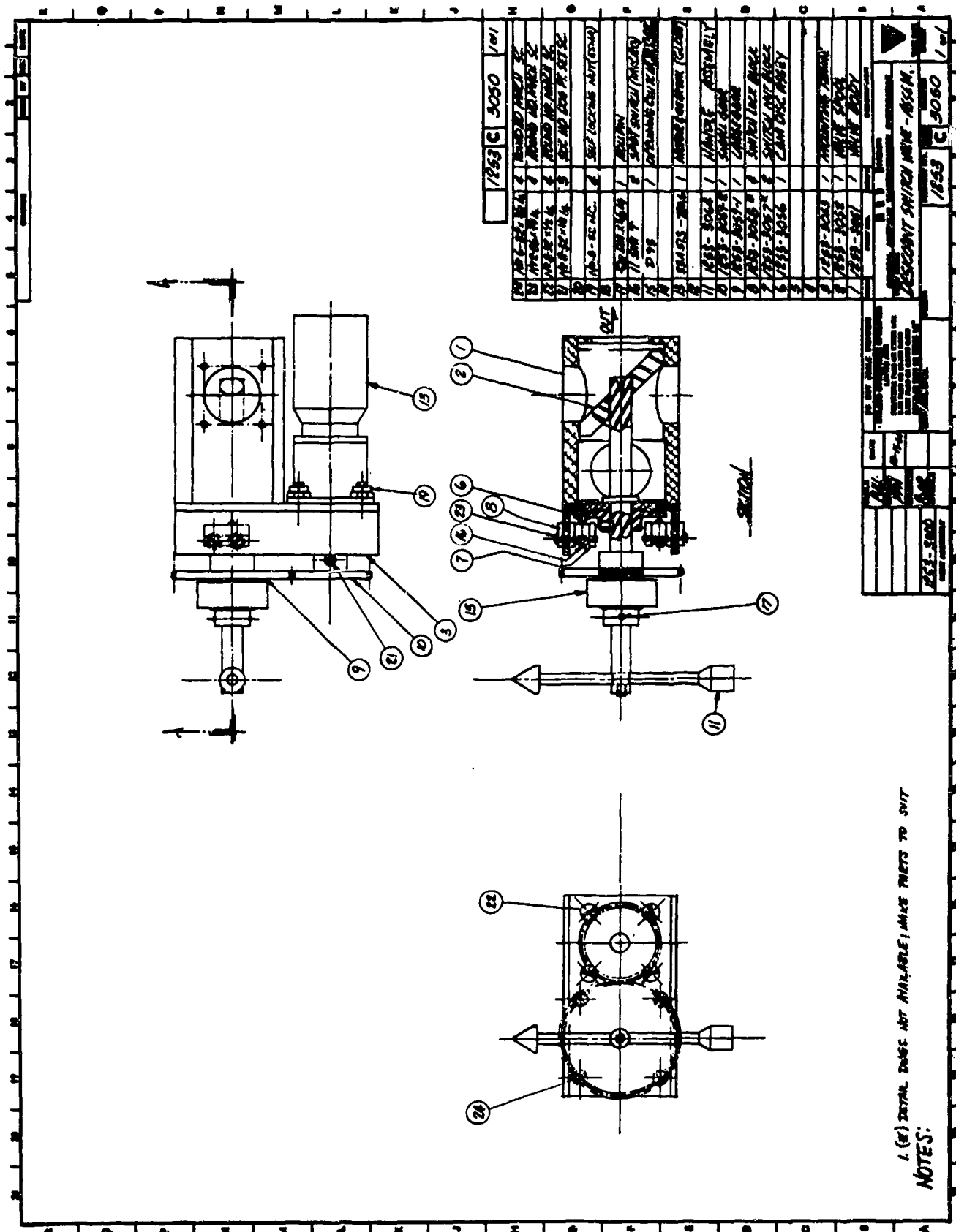


Figure 7. DESICCANT SWITCH VALVE

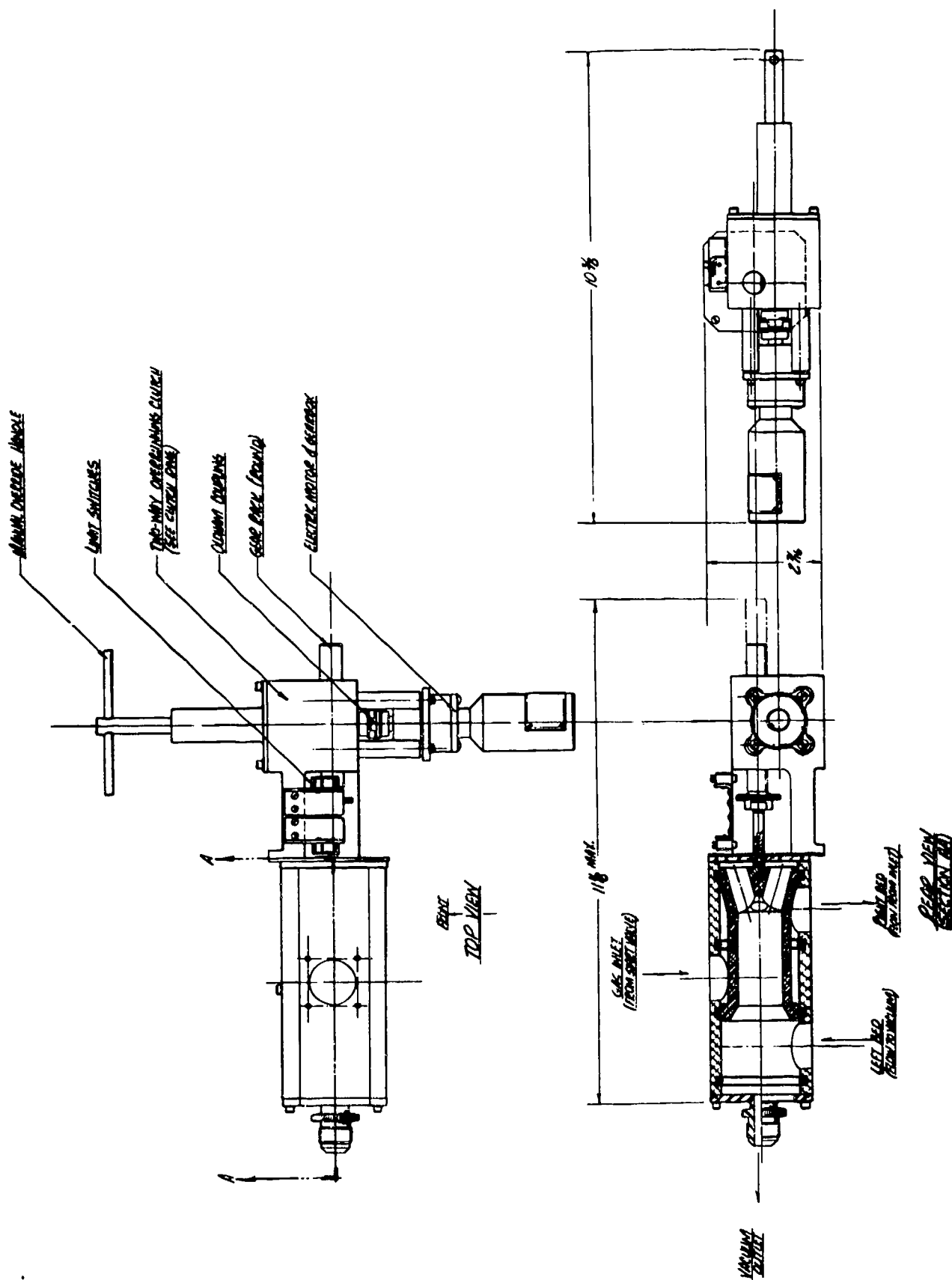


Figure 8. ZEOLITE VACUUM SWITCH VALVE

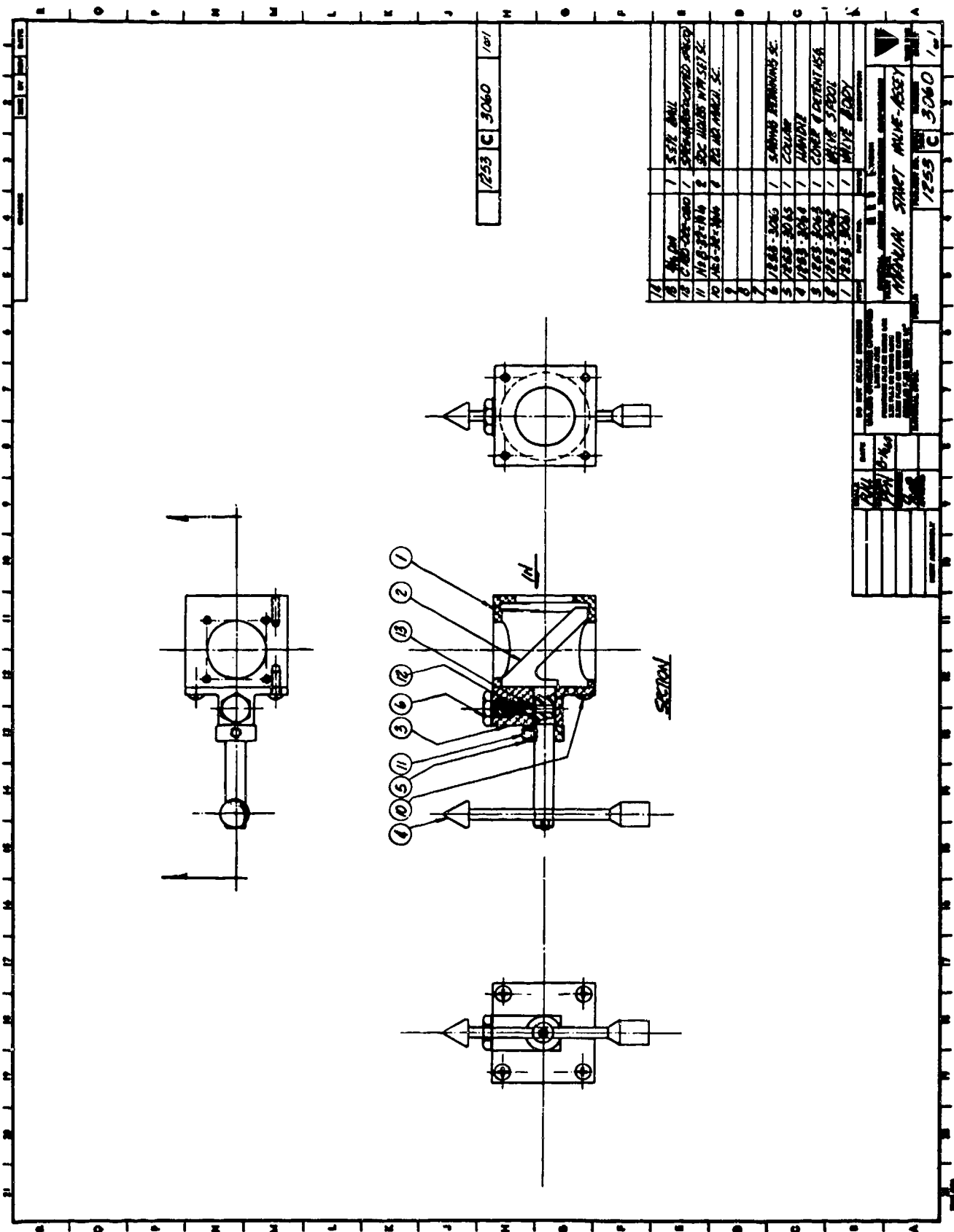


Figure 9. GAS START VALVE

zeolite beds during start-up. The desiccant beds can be dried out and readied for use without circulating air through the zeolites. Consequently, the zeolite beds may be evacuated and heated to temperature somewhat higher than those prevailing during normal operation, thus more effectively desorbing water from the zeolites.

A 3-port, 2-position configuration is necessary to provide the required flow paths. Flow from the single inlet is diverted to one or the other side ports. In the "start" position one port of the valve returns the entering gas to the desiccant beds; in the "run" position the other port feeds the dehumidified gas to the zeolite beds for carbon dioxide adsorption. A ball detent aids in locating the two positions, and the same arrow-shaped handle shows whether the valve is set for the start or run cycle.

Liquid Switch Valve

A four-way motor operated switch valve alternates the heated and cooled liquid streams to the in-bed heat exchangers. The valve is a 90° - reversible plug valve with a tapered stainless steel rotor and Teflon® sleeved housing. Identical valves are used in each loop. The motor operates from a 115-volt, 60-cps, single-phase source.

Carbon Dioxide Purification Valve

A three-way diverter valve, located at the carbon dioxide transfer pump outlet, directs interstitial gases from a regenerating zeolite bed back to the cabin atmosphere. When the bed pressure drops to below 50 mm Hg absolute the valve actuates to direct the flow to the carbon dioxide storage tank. The valve is solenoid operated from a 115-volt, 60-cps, single-phase source.

Liquid Start Valve

A three way selector valve is used in the zeolite liquid loop to bypass a portion of the flow around the cooler during start up. The valve is similar to the liquid switch valves except the plug is drilled for three-way porting.

Vacuum Selector Valve

A three-way ball valve is located between the zeolite switch valve and vacuum pumps. For normal operation the valve connects to the carbon dioxide transfer pump; for start-up it connects to the external vacuum pump/freeze trap system. The valve is stainless steel with Teflon® seats.

Internal Display Panel

A secondary display panel on the unit provides parallel indication of the pilot lights and contains temperature and pressure gauges for readouts of random measurements. The panel also contains gauges for

indicating carbon dioxide regeneration pressure and carbon dioxide storage pressure.

Electrical Controls

The system electrical controls are housed within an external console which connects to the system through two cables. The console is shown mounted on the saw horse (right) in Figure 13. The controls consist of three desiccant timers, two zeolite timers, two indicating temperature controllers, and switch/circuit breakers for the components and the main control. A differential pressure switch located externally on the chamber wall and connected internally to the vacuum desorption line controls the switching of the carbon dioxide purification valve.

The desiccant cycle duration timer switches the 4-way, desiccant liquid valve and actuates the valve delay timer and gas heater duration timer. When the valve delay timer expires it switches the desiccant gas valve and restarts the cycle duration timer. The heater timer controls the maximum duration which the gas heater is on.

The zeolite cycle duration timer switches the zeolite liquid valve and actuates the zeolite delay timer. After the latter timer has expired, it switches the zeolite gas valve and restarts the cycle duration timer.

The timers are wired so that the cycles may be operated independently of each other. The cycle duration timers are interconnected by a synchronizer switch which also permits operation on synchronous cycles controlled by the desiccant cycle duration timer.

The liquid pumps, main blower, heaters, dehumidifier blower, and carbon dioxide transfer pump are controlled by switch/circuit breakers located on the main control panel. The system wiring diagram is shown on Figure 10.

SECTION III

OPERATION AND TESTING

SYSTEM OPERATION

The initial operation of the system was concerned with functional performance of all of the system components without actual processing to dry the incoming air or to remove carbon dioxide. The system components were tested individually and were adjusted to meet operational requirements. The complete electrical circuitry was tested by individual function and then as a system to insure that cycling and heating controls were synchronized, and that the instrumentation and control panel components were operating correctly. During this shakedown testing, modifications to the system were the addition of motor starting switches for the blower and for the carbon dioxide transfer pump and the addition of a pressure gauge in the zeolite liquid loop.

Start-up

In start-up operation the primary objectives are to remove all moisture from the zeolite beds, and similarly to prepare the desiccant beds for removing the water vapor from the incoming gas stream. The zeolites are water-desorbed by heating to 400-450°F and evacuating to 500 microns or less, preferably to between 100 and 200 microns. The desiccant beds are prepared for use by passing cabin gas through one bed, heating the partially dried process gas, and passing it out through the other bed to remove water. With cyclical reversal of gas flow direction the beds gradually reach the point where the gas leaving the adsorbing bed is at a dewpoint below -46°C (63 ppm).

Desorbing of the zeolite beds is accomplished by vacuum-pump evacuation and continuous circulation of silicone fluid through the liquid heater and the beds. A small portion of the liquid passes through the cooler to maintain the pump inlet at less than 350°F. The bypass flow is directed by the manual start valve. No gas flows through the zeolite beds during start-up.

The detail procedures for start-up operation are described in the Operating Instructions and Maintenance Manual. (Reference 4)

Normal Operation

In normal operation the zeolite beds are desorbed of water after start-up operation and ready for carbon dioxide adsorption. Similarly after the initial start-up operation, the desiccant beds are cycling properly and providing dried gas having a -46°C dewpoint (63 ppm) or lower.

Adsorption of carbon dioxide is accomplished by passing dried gas through the cooled zeolite bed. During normal operation the heat transfer liquid is cooled in the liquid cooler and the liquid, in turn, cools the adsorbing bed. The liquid manual start valve is set so that all the recirculating liquid passes through the cooler. While the cool zeolite bed is being cooled and is adsorbing carbon dioxide, the opposite bed is being heated and simultaneously subjected to vacuum by the carbon dioxide transfer pump. At the expiration of the cycle the appropriate gas and liquid valves operate to reverse the flow directions and the freshly regenerated zeolite bed becomes the adsorbing bed while the opposite bed becomes the desorbing bed.

The detail procedures for normal operation are described in the Operating Instructions and Maintenance Manual. (Reference 4)

INSTRUMENTATION AND MONITORING

The calibration and performance tests were conducted in GARD's 500 cu. ft. Internal Environmental Simulator (IES). The schematic diagram of the test set-up is shown in Figure 11. Figure 12 shows the carbon dioxide removal system installed in the IES and instrumented for the tests. The arrangement of the instrumentation and controls is shown by the photograph in Figure 13.

The test measurements recorded and instruments used are listed in Table I. The location of temperature measurements at the various locations on the system are designated on the test set-up schematic diagram.

With the exception of the cabin psychrometer, the instruments provided a direct readout or a percentage indication of the appropriate measurement. The wet-bulb and dry-bulb psychrometer readings require further calculations to determine the humidity. Standard psychrometric charts or tables may be used when the IES atmosphere composition is at 1 atmosphere pressure. For total pressures other than 1 atmosphere and gas compositions differing from air, the relationship between humidity and wet-bulb and dry-bulb temperature deviates from the commonly tabulated values. This is discussed further in the Appendix.

Carbon dioxide was fed into the IES from a cylinder and controlled by a micrometer handle needle valve. The carbon dioxide was measured by a rotameter for a rough instantaneous reading and also by an integrating wet-test meter for an accurate timed reading.

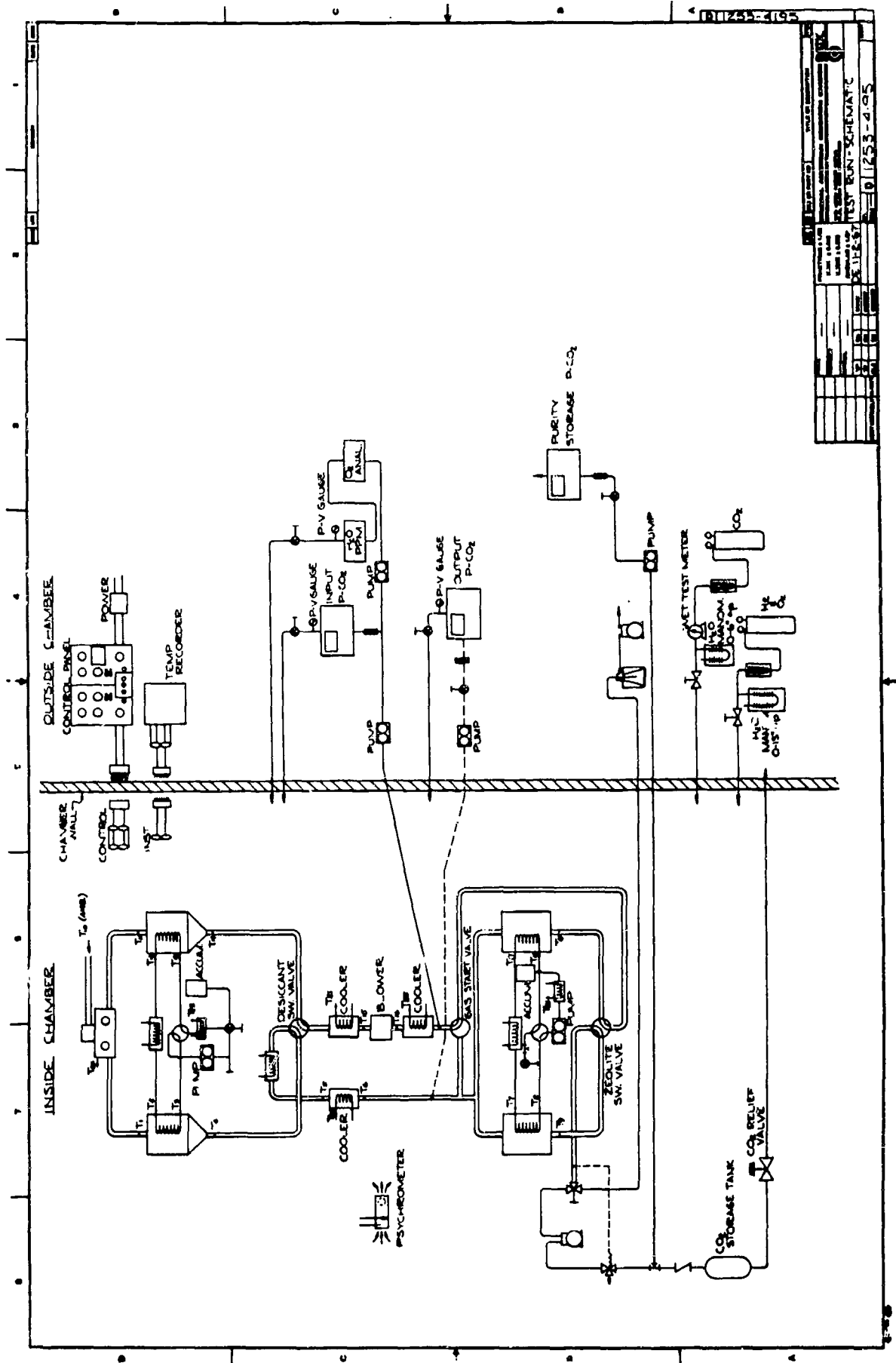


Figure 11. TEST RUN SCHEMATIC



Figure 12. CARBON DIOXIDE REMOVAL SYSTEM TEST INSTALLATION



Figure 13. CARBON DIOXIDE REMOVAL SYSTEM TEST INSTRUMENTATION SET-UP

TABLE I
TEST PARAMETERS AND INSTRUMENTATION

Cabin Total Pressure	Wallace & Tiernan Absolute Pressure Gauge
Cabin Temperature	Thermocouple & Recorder
Cabin Water Vapor Partial Pressure	Wet-bulb, Dry-bulb Psychrometer
Cabin Carbon Dioxide Partial Pressure	MSA Lira Infra-red Analyzer
Cabin Oxygen Partial Pressure	Beckman Oxygen Analyzer
Zeolite Inlet Dewpoint	Beckman Electrolytic Hygrometer
Zeolite Outlet Carbon Dioxide Partial Pressure	MSA Lira Infra-red Analyzer
Process Temperatures	Thermocouples & Multipoint Recorder
Carbon Dioxide Storage Pressure	System-Mounted Pressure Gauge
Carbon Dioxide Storage Purity	MSA Lira Infra-red Analyzer
Zeolite Regeneration Pressure	Hg Manometer (External to IES) and System Mounted Gauge

Oxygen and/or helium was fed through rotameters from their respective cylinders as required for the desired cabin atmosphere composition. Cabin temperature was controlled by standard air conditioning techniques. Cabin humidity was controlled by on-off operation of the IES humidifier or the dehumidifier as required to maintain the desired level. When the IES pressure was less than atmospheric pressure, the trim pump (sealed, diaphragm pump) was operated to compensate for the IES in-flow leakage. The pump discharge flow was measured in a Sprague positive displacement gas meter. This was necessary so that the actual carbon dioxide feed rate could be increased to offset the amount pumped out in the trim flow.

TEST RESULTS

The carbon dioxide removal system was initially operated at atmospheric pressure to determine (1) the proper desiccant and zeolite cycle times, (2) the proper switch valve delay times, (3) the optimum heater settings, and (4) the proper heat transfer liquid flow rate. During calibration testing the system was also operated at one-half atmosphere in air to simulate the reduced pressure oxygen-nitrogen test and at one-third atmosphere in air to simulate the reduced pressure oxygen-helium test. At each of these conditions the above cycle times, heater settings, and flow rates were varied to determine an optimum combination. The system reduced the IES carbon dioxide level from 7.5 mm Hg to 6.5 mm Hg with a 4.5 man rate input at 250 mm Hg pressure (one-third atmosphere air) during a 10 hour run. During the course of optimizing the cycle times and heater input levels, the controls were arranged to operate the desiccant and zeolite cycles in synchronization. By disconnecting the coolant to the return gas cooler and operating with synchronized cycles, the heat from a freshly regenerated zeolite bed was transferred directly to the new regenerating desiccant bed. This resulted in repetitive performance of the desiccant beds with less electrical heater input and lower heat rejection in the gas coolers.

All calibration and performance tests were conducted with Linde Type 5AXW, one-sixteenth diameter zeolite cylinders as the carbon dioxide adsorbent and Davison grade 08 (12-28 mesh) silica gel as the desiccant.

Performance Tests

The 6-day continuous unmanned performance test was started on 11 November and completed on 20 November 1967. During this time the system operated without maintenance or interruption. Prior to the start of the performance tests, the system was operated overnight in the start-up mode. This resulted in a desiccant outlet of five and one-half (5-1/2) ppm moisture content and zeolite regeneration of 400 to 450 microns at an average bed temperature of 320°F to 350°F. After the start-up operation was completed the system controls were changed to the operating mode according to the procedure described in the Operating Manual (Reference 4) and the system operated only at normal operating conditions thereafter without any start-up regenerating during the performance tests. The order in which the tests were conducted was (1) test at 360 mm Hg, nitrogen diluent, (2) test at 360 mm Hg, helium diluent, and (3) test at atmospheric pressure. The oxygen-helium test was performed in air-helium with all conditions the same except air was substituted for oxygen. The IES inleakage of ambient air precluded the test being run with 45% oxygen-55% helium. By supplying relatively large make-up flows of both helium and oxygen the nitrogen concentration could be minimized but at a sacrifice in accurately monitoring the net carbon dioxide input rate. Since the properties of oxygen and air are practically identical, it was agreed to operate in air-helium in place of oxygen-helium. The oxygen-nitrogen test at 360 mm Hg

total pressure was performed with 160 mm Hg partial pressure oxygen and nitrogen make-up gas, which demonstrated the system's capability of operating in high oxygen concentration atmospheres.

At the beginning of each of the three tests, the IES carbon dioxide concentration was brought up to 7.6 mm Hg. Carbon dioxide was then added during the tests at a rate of 10.4 + lb/day (equivalent to output of a 4-man crew). During the oxygen-nitrogen test at 360 mm Hg the IES humidity varied from 11.4 to 13.2 mm Hg with a median level of 11.8 mm Hg. Over the 2-day period, the carbon dioxide feed averaged the equivalent of a 4.2 man rate and the partial pressure carbon dioxide varied from 5.7 to 7.2 mm Hg with a median level of 6.1 mm Hg. The desiccant outlet moisture content varied between 25 and 60 ppm (equivalent) and the median level was 38 ppm. The oxygen-nitrogen test results at 360 mm Hg are shown in Table II.

The air-helium test was conducted at 350 mm Hg total pressure. During the 2-day test, the carbon dioxide feed was the equivalent of a 4.3 man rate and the system removed it at a rate which maintained the IES carbon dioxide level between 6.6 and 7.4 mm Hg with a median level of 7.1 mm Hg. The IES humidity varied between 11.7 and 13.3 mm Hg with a median level of 12.7 mm Hg. When operating at the optimized combination of timer settings and regeneration temperature levels, the desiccant outlet moisture content varied between 31 and 60 ppm (equivalent) when averaged over the length of the cycle; the median level was 53 ppm (equivalent). The air-helium test results at 350 mm Hg are shown in Table III.

The IES atmosphere composition for the test at 750 mm Hg was standard air with the humidity varying between 11.7 and 13.6 mm Hg. The desiccant outlet moisture content varied between 13 and 40 ppm with a median level of 20 ppm. During the 2-day test, the carbon dioxide feed averaged the equivalent of a 4.1 man rate and the system maintained the IES carbon dioxide level between 4.4 and 6.8 mm Hg with a median level of 4.6 mm Hg. The atmospheric pressure test results are given in Table IV.

During the performance tests, the system recovered 100% of the available carbon dioxide removed from the IES atmosphere; the recovered carbon dioxide was pumped to storage at 16.0 psia. The regeneration vacuum varied between 10 and 35 mm Hg during the cycle. The carbon dioxide purity averaged 93% for a typical cycle at atmospheric pressure and the corresponding readings were higher at 360 mm Hg. A typical curve of regeneration vacuum vs. cycle time is shown in Figure 14.

Table II

TEST AT 360 mm Hg, NITROGEN DILUENT

Date	Time	IES Atmosphere						Temp (°F)	Gas to Zeolites (equiv. ppm H ₂ O)	CO ₂ Feed (cc/min)
		Press (mmHg)	pO ₂ (mmHg)	pHe (mmHg)	pH ₂ O (mmHg)	pCO ₂ (mmHg)	pN ₂ (mmHg)			
11 Nov	1320 ¹									
11 Nov	1500	362	152	- -	12.7	7.24	bal.	78	25	1890
	1700	360	162	- -	11.4	5.7	bal.	79	60	1891
12 Nov	0500	420 ²								
	0600	356	144 ³	- -	11.4	5.7	bal.	79	34	1890
	1700	362	145	- -	13.2	6.0	bal.	77	44	1990
13 Nov	0930	355	147	- -	12.3	6.2	bal.	79	37	1900
	1300	360	165	- -	11.8	6.1	bal.	79	55	1890
	1700	362	175	- -	11.8	6.2	bal.	78	40	1900
14 Nov	0700	360	176	- -	11.5	6.1	bal.	78	32	2018

¹ Evacuated to 250 mmHg then backfilled to 360 mmHg with oxygen
IES pCO₂ = 7.6 mmHg

² Recorders & Trim pump not functioning; C/Breaker tripped.
Operated humidifier to raise IES Humidity.

³ Increased O₂ make-up feed.

Table III

TEST AT 350 mmHg, HELIUM DILUENT

		IES Atmosphere							Zeolites (equiv. ppm H ₂ O)	CO ₂ Feed (cc/min)
Date	Time	Press (mmHg)	pO ₂ (mmHg)	pHe (mmHg)	pH ₂ O (mmHg)	pCO ₂ (mmHg)	pN ₂ (mmHg)	Temp (°F)		
15 Nov	1800 ¹	350	31	196	13.3	7.2	bal.	79	31	1940
16 Nov	0700	345	36	170	11.7	6.6	bal.	77	60	1950
	1400	344	31	180	12.5	6.7	bal.	78	100 ²	1940
	2000	344	29	190	13.0	6.9	bal.	79	50	2010
17 Nov	0840	344	29	190	12.7	7.2	bal.	79	55	2000
	1340	339	29	185	12.7	7.4	bal.	79	60	1950
	1840	340	30	180	13.2	7.1	bal.	80	50	1930

¹ IES evacuated to 160 mmHg, then backfilled to 350 mmHg with He.

² Experimented with alternate desiccant cycles.

Table IV

TEST AT ATMOSPHERIC PRESSURE

Date	Time	IES Atmosphere							Gas to Zeolites (equiv. ppm H ₂ O)	CO ₂ Feed (cc/min)
		Press (mmHg)	pO ₂ (mmHg)	pHe (mmHg)	pH ₂ O (mmHg)	pCO ₂ (mmHg)	pN ₂ (mmHg)	Temp (°F)		
18 Nov	1110	741	150	- -	13.6	6.8	bal.	77	40	1870
	2230	746	152	- -	12.6	4.6	bal.	77	15	1820
19 Nov	0715	749	154	- -	11.7	4.6	bal.	76	18	1830
	1130	751	154	- -	11.7	4.6	bal.	77	35	1870
20 Nov	0900	749	154	- -	11.7	4.4	bal.	77	13	1940
	1110	749	154	- -	12.8	4.55	bal.	78	22	1900

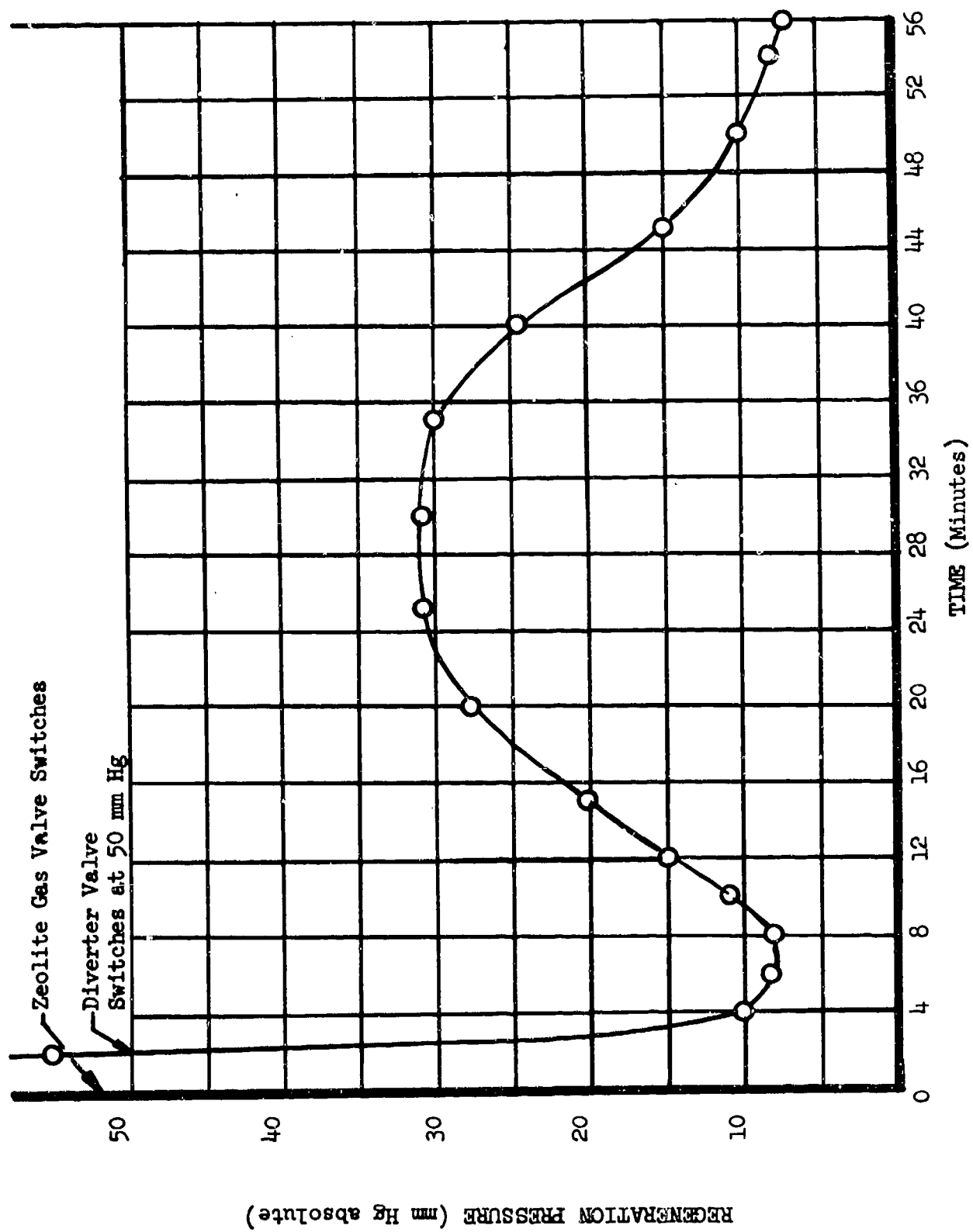


Figure 14. CARBON DIOXIDE DESORPTION

The system parameters which were varied during calibration testing were determined to be optimized at the following values:

	<u>760 mm Hg</u> <u>Test</u>	<u>360 mm Hg,</u> <u>N₂ Diluent</u>	<u>360 mm Hg</u> <u>He Diluent</u>
Desiccant & Zeolite Cycle Duration, (synchronized cycles), min.	56	57	57
Desiccant Gas Heater Duration, min.	20	20	20
Desiccant Valve Delay, min.	1	2	4
Zeolite Valve Delay, min.	2	2	2
Desiccant Regeneration Temp., °F	550	450	400
Zeolite Regeneration Temp., °F	600	600	600

The same heaters were used in all the tests; the zeolite liquid heater provided 1080 watts total, the desiccant liquid heater output was 750 watts total, and the desiccant gas heater provided 300 watts.

The temperatures which are directly related to the performance of the desiccant bed and zeolite bed are shown in Figure 15, 16 and 17 for the oxygen-nitrogen test, air-helium test, and the atmospheric pressure test, respectively. Examining the desiccant inlet gas temperatures in any of the figures it is shown that the gas leaves the dehumidifier at 50-55°F. The heat of adsorption in the desiccant bed is removed by the cooled heat transfer liquid and the exiting gas temperature from the adsorbing bed remained cool after the sensible heat was initially removed. The gas entering the regenerating desiccant bed peaked between 250°F and 275°F when operating at atmospheric pressure and between 225°F and 275°F when operating at 360 mm Hg. The gas temperature exiting from the regenerating bed approached 150°F during the latter part of the cycle. The liquid temperature in the regenerating zeolite bed averaged about 300°F over the cycle. The gas temperature entering the zeolite adsorbing bed (not shown in the figures) was maintained at 60-65°F during all tests.

The original system (Reference 3) which was tested in air at both sea level pressure and at 7.7 psia had approximately the same carbon dioxide removal capacity at sea level as the system described in this report. In that system, the desiccant beds were passively heated and cooled by the process gas stream. A significant difference is shown, however, when operating at reduced pressure levels. Whereas, the original system could maintain 7.6 mm Hg carbon dioxide partial pressure for only a short duration, this system

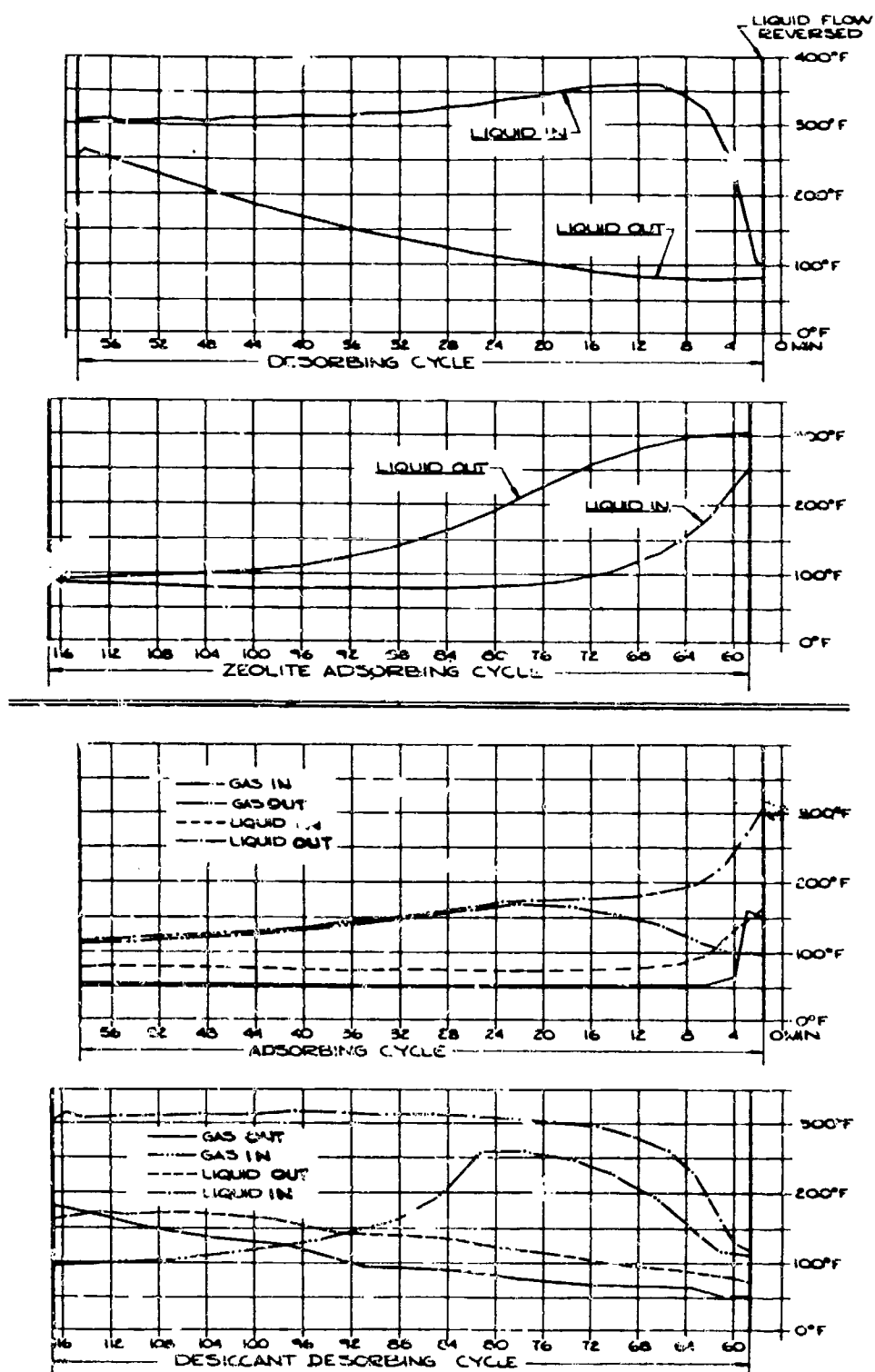


Figure 15. TEMPERATURE CYCLES AT 360 mm Hg, NITROGEN DILUENT

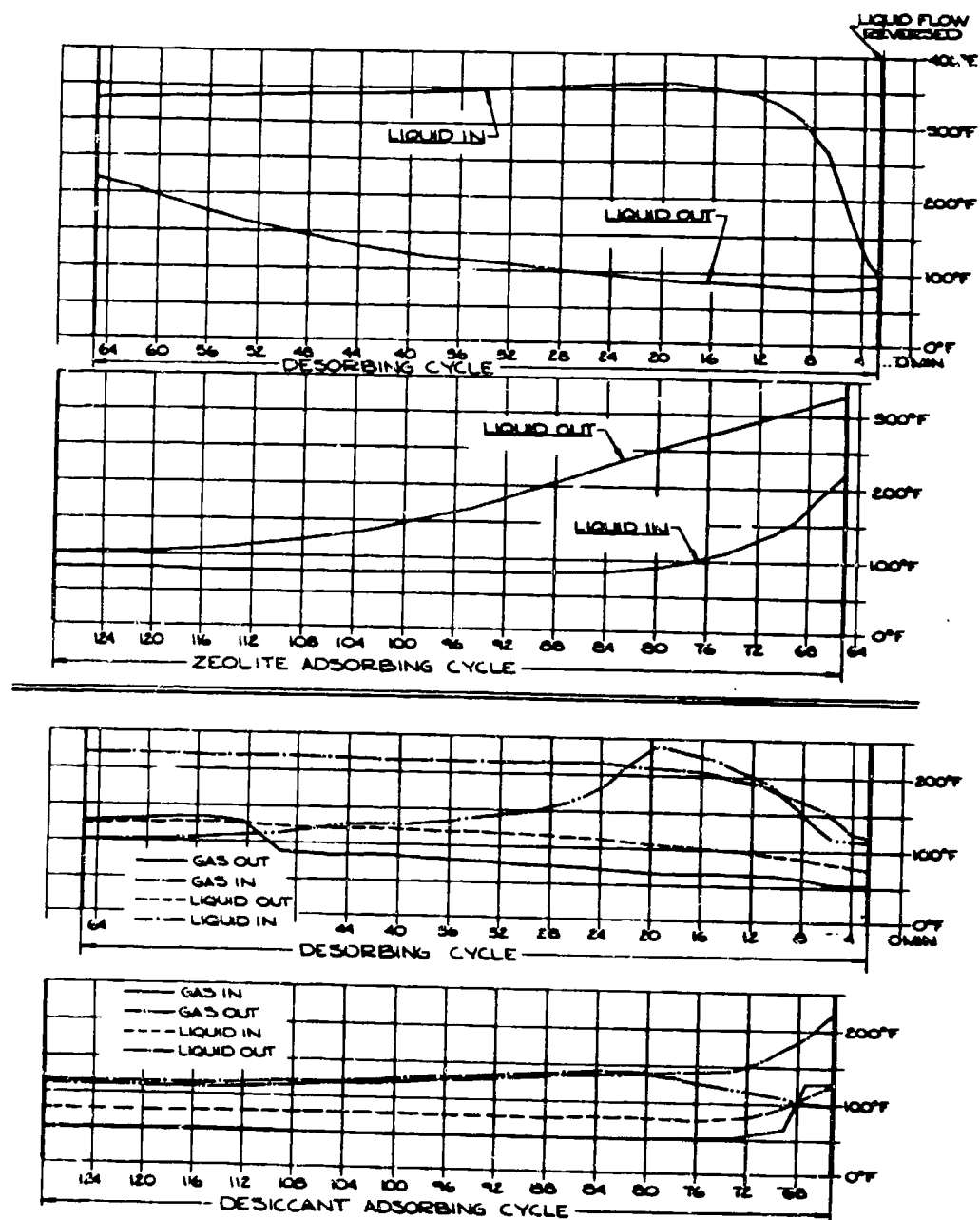


Figure 16. TEMPERATURE CYCLES AT 350 mm Hg, HELIUM DILUENT

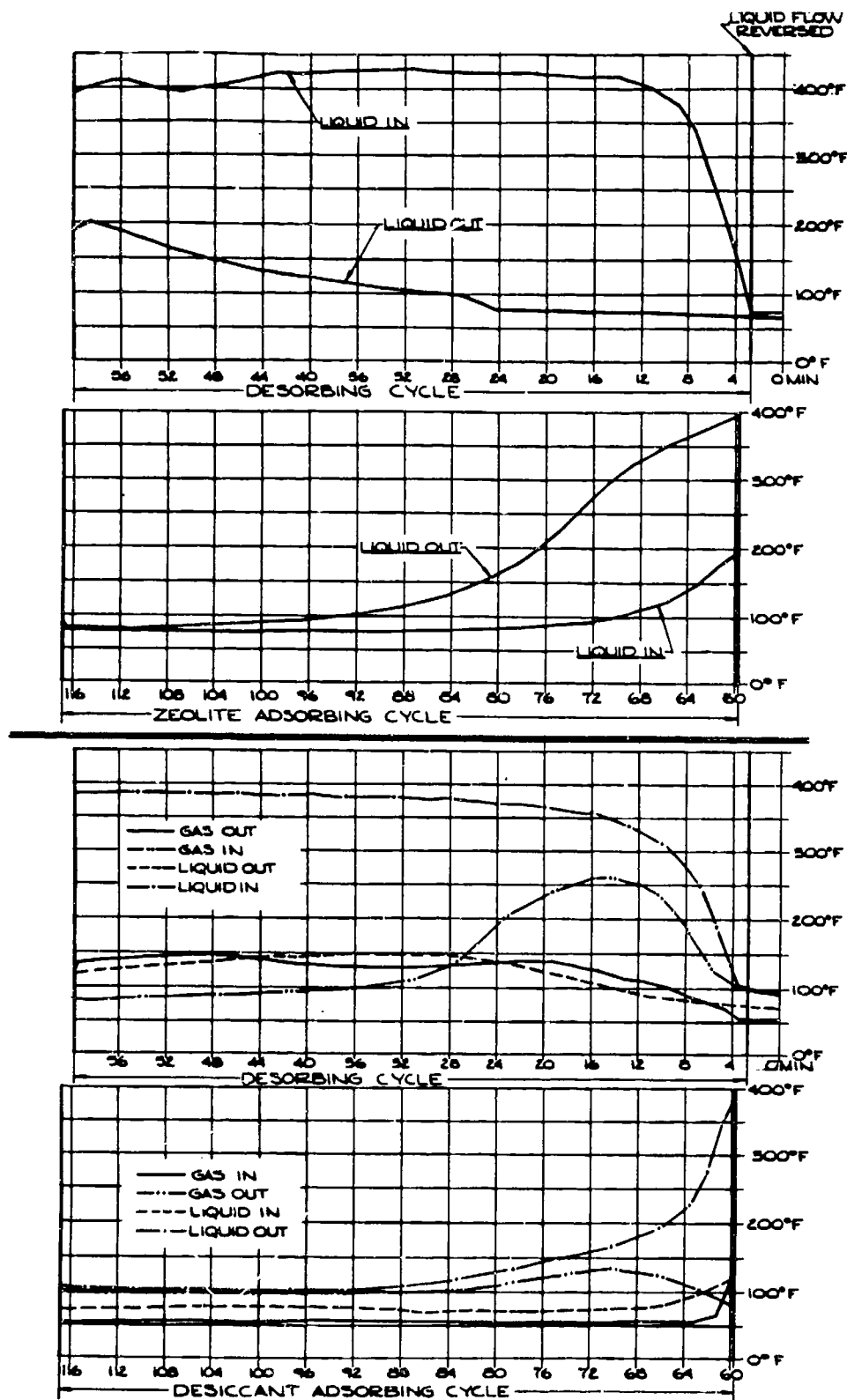


Figure 17. TEMPERATURE CYCLES AT ATMOSPHERIC PRESSURE

maintained a median level of 6.1 mm Hg with nitrogen diluent and 7.1 mm Hg with helium diluent. This is because the zeolite beds in the original system were gradually being saturated with water vapor because of its desiccant bed inefficiency at reduced pressure. The test data shows that the desiccant outlet moisture content of the original system was as high as 1500 ppm with even occasional higher peaks. For this system, with desiccant in-bed heat exchangers, the corresponding value was 60 ppm.

The zeolite beds were sized to operate for 30 minutes of adsorption and then 30 minutes of vacuum desorption. The sizing calculations were based on Type 5A zeolites as the adsorbent. The manufacturer, Linde Division of Union Carbide recommended the newer Type 5AXW material but as yet does not have the loading capacities for it. It is known to be higher than the Type 5A zeolites and probably accounts for the fact that the system could operate effectively for 1-hour adsorption cycles.

SECTION IV

CONCLUSIONS AND RECOMMENDATIONS

Based on the fabrication, testing and operation of the Regenerable Carbon Dioxide Removal System the following observations have been made concerning various features of the system:

1. At four-man capacity the system will maintain the carbon dioxide partial pressure between 4 and 5 mm Hg absolute for atmospheric pressure operation, and between 6 and 7 mm Hg for 350 mm Hg operation.
2. At atmospheric pressure the system can handle greater than four-man capacity, estimated at six-man capacity, and maintain the carbon dioxide partial pressure at 7.6 mm Hg absolute.
3. The maximum operating humidity level for the capacities shown in 1 and 2 above was 13.0 mm Hg partial pressure for all cabin pressures and gas compositions.
4. At four-man capacity the system will maintain the carbon dioxide partial pressure between 6 and 7 mm Hg absolute at 250 mm Hg total chamber pressure.
5. Two desiccant beds, continuously regenerated and alternated, are adequate for drying the incoming gas stream to the required dew point level of -46°C (63ppm).
6. Two solid zeolite beds, continuously regenerated and alternated, are adequate for removing carbon dioxide in the gas stream to provide the required carbon dioxide level in the chamber.
7. A liquid-filled in-bed heat-exchange system satisfactorily provided both the heating and cooling necessary for the cycled regeneration of each desiccant and each zeolite bed.
8. The system recovered 100% of the carbon dioxide available at an average purity greater than 90%.
9. The specially designed desiccant and zeolite switch valves performed reliably and continuously in switching the gas flow and the desorption vacuum flow.
10. The reliability of the complete system was demonstrated by operation for 390 continuous hours during calibration and performance testing and without maintenance or interruption.
11. The system was not optimized for power and weight; the total average power required is 4000 watts, and the total weight including the mounting frame approximates 250 pounds.
12. The electrical cycling controls performed automatically and continuously without incident, and the time cycles were repeatable and constant.

The Regenerable Carbon Dioxide Removal System described herein may be operated over a wide range of cabin environments with flexibility on varying the system operating parameters. It may be used to determine the thermodynamic requirements of a flight type system which could be used for spacecraft applications. Since it is not optimized for power and weight, the applicable data which may be obtained is the heating and cooling rates, flow rates, and temperatures and pressures at various locations throughout the system for a particular cabin gas composition. In particular, the test results of this program demonstrated the need for in-bed heat exchangers in the desiccant subsystem when operating at reduced pressure levels and demonstrated that when desiccant in-bed heat exchangers are utilized the desired gas dryness levels are achieved.

APPENDIX

DETERMINATION OF WATER VAPOR PARTIAL PRESSURE BY WET-BULB AND DRY-BULB TEMPERATURE MEASUREMENT

The relationship between partial pressure and wet-bulb and dry-bulb temperatures for water vapor in gas is expressed by:

$$P_{wb} - P = \left(\frac{h_G}{k_y} \right) \left(\frac{R_{H_2O}}{R_{gas}} \right) \left(\frac{P_{gas}}{\lambda_{H_2O}} \right) \times (t_{db} - t_{wb})$$

Where P = water vapor partial pressure of mixture

P_{wb} = saturation pressure at wet-bulb temperature

h_G = convective heat transfer coefficient

k_y = mass transfer film coefficient

R = gas constant

P_{gas} = total pressure of dry gas

λ_{H_2O} = latent heat of vaporization at wet-bulb temperature

t_{db}, t_{wb} = dry-bulb temperature, wet-bulb temperature

It has been calculated and experimentally confirmed that for air/water vapor mixtures at normal temperatures,

$$\frac{h_G}{k_y} = .242 \quad (\text{Reference } 8)$$

$$\text{Thus, } P_{wb} - P = \frac{(0.3895)}{H_2O} (P_{gas}) \times (t_{db} - t_{wb}) \text{ for air}$$

This equation may be used for 45% oxygen - 55% nitrogen gas compositions because their applicable properties are practically identical to those of air.

$$\frac{h_G}{k_y} = (C_s) \left(\frac{Sc}{Pr} \right)^{0.56} = (C_s) \left(\frac{k}{(C_s) \rho (D_{AB})} \right)^{0.56} \quad (\text{Reference 9})$$

Where C_s = humid heat, $\frac{\text{Btu (for vapor--gas mixture)}}{(\text{lbm dry gas}) (^{\circ}\text{F})}$

Sc = Schmidt number

Pr = Prandtl number

k = thermal conductivity of dry gas

ρ = density

D_{AB} = water vapor/gas diffusion coefficient

For the oxygen-helium mixture: $C_s = 0.37 \frac{\text{Btu}}{(\text{lbm}) (^{\circ}\text{F})}$

$k = 0.048 \frac{\text{Btu}}{(\text{hr}) (\text{ft}) (^{\circ}\text{F})}$

$\rho = 0.021 \frac{\text{lbm}}{\text{ft}^3}$

$D_{AB} = 7.2 \text{ ft}^2/\text{hr}$

$R_{\text{gas}} = 85.8 \frac{(\text{ft}) (\text{lbf})}{(\text{lbm}) (^{\circ}\text{R})}$

Thus, $P_{wb} - P = \frac{(.34)}{\lambda_{H_2O}} \frac{(P_{\text{gas}})}{R_{\text{gas}}} \times (t_{db} - t_{wb})$ for the oxygen-helium mixture.

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<p>The development of a regenerable carbon dioxide removal system is discussed. The system utilizes solid zeolites to adsorb carbon dioxide and silica gel for predrying the gas stream. The system is completely regenerable, operates automatically and continuously, and provides for storage of the removed carbon dioxide. It is operable over a wide range of cabin environments and provides flexibility in varying the system operating parameters. It may be used to determine the thermodynamic requirements of a flight-type system for a particular cabin gas composition. The system can remove the carbon dioxide from four crewmen and maintain the carbon dioxide partial pressure between 4 and 5 mm Hg absolute at atmospheric pressure operation and between 6 and 7 mm Hg when operating at 350 mm Hg total pressure. It has this removal capacity when the cabin atmosphere is composed of 13 mm Hg water vapor partial pressure, 160 mm Hg oxygen partial pressure and either nitrogen or helium as the makeup gas. An external control console is provided which permits the system to be operated in an unmanned chamber. The system is not optimized for power and weight; as a laboratory model the total average power required is 4000 watts and the total weight including the mounting frame is 250 pounds.</p>			

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